"On Changes in Elastic Properties produced by the sudden Cooling or 'Quenching' of Metals."

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(Being part of a Thesis submitted for the degree of Doctor of Science, Glasgow University.)

It is well known that when steel is quenched from a red heat, its elastic properties suffer a profound change, the material becoming extremely hard and brittle. It is also known that quenched steel, when tested under tension, exhibits no distinct yield-point, Hooke's law is departed from quite gradually until abrupt fracture occurs at a high stress. The effect produced on copper by quenching has been considered, at least in some respects, the reverse of that produced in steel. The experiments to be described in this paper, however, show that with mild steel, soft iron, copper, zinc, aluminium, brass, and so probably with all metals, quenching from high temperatures produces effects which are analogous to one another; in all cases there is a marked loss of elasticity produced by quenching, low loads producing appreciable permanent extensions or "sets."

The method of experimenting need not be described in detail here, as it was identical with that described in the paper by the present author on "The Tempering of Iron hardened by Overstrain."* The new 5-ton testing machine of the Cambridge Engineering Laboratory was however employed for many of the experiments in preference to the large 50-ton gun machine previously used. Small strains of extension and of compression were measured by instruments of Professor Ewing's design—extensions by means of the 4-inch extensometer illustrated on p. 2, 'Phil. Trans.,' A, 1902, compressional strains by the instrument illustrated on p. 79 of Professor Ewing's book on "The Strength of Materials." The heating of the specimens was obtained by means of the gas furnace used in the earlier experiments on tempering after overstrain, temperatures being measured by a Callendar's direct-reading platinum resistance pyrometer. The hot specimens were "quenched" by plunging them vertically into a large tank of cold water.

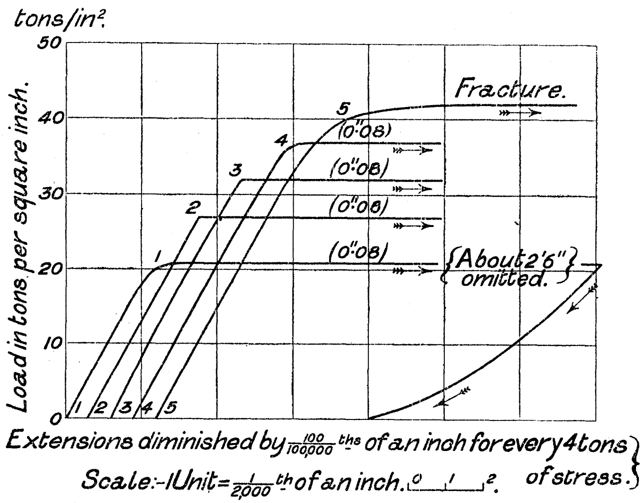
The results to be recorded in this paper may be gathered from an examination of the accompanying series of diagrams. The diagrams give with one exception (Diagram 4) the results of tension tests, and it need only be remarked that all the stress-strain curves have been "sheared back" in the manner suggested by Professor Ewing, and

* 'Phil. Trans.,' A, 1902, p. 1.

fully described in a paper by the present author "On the Recovery of Iron from Overstrain."* The amount by which the curves have been sheared back is marked at the foot of each diagram. Thus, in Diagram No. 1, $\frac{100}{100000}$ths of an inch have been deducted from the extension of the 4-inch length for every 4 tons of stress. For example, the extensometer readings for stresses of 4, 8, and 12 tons per square inch were 120, 240, and 360 respectively; the numbers actually plotted were 20, 40, and 60. The origin for the measurement of extensions has been displaced for the various curves of each diagram in order to avoid a confusion of the curves.

Diagram No. 1 shows the elastic properties of an annealed specimen of mild steel. The specimen was subjected to a series of tension tests, the load in each test being carried just to a yield-point. Recovery from the overstrains produced by the passing of the successive yield-points was effected by heating the specimen to temperatures of from

Diagram No. 1.—(Mild steel-annealed.)



Diameter of specimen = 0″·331.
Length under test = 4″·00.
Fracture occurred at 40 tons per square inch original area. Extension (including all yield-points) = 0″·38 on 4 inches.

200° to 250° C. The specimen broke at the fifth yield-point, the breaking stress being 42 tons per square inch, or about 40 tons per square inch taking the original area of the specimen. After the passing of each yield-point the diameter of the specimen was of course

* 'Phil. Trans.,' A, vol. 193, 1899.

slightly reduced; this was allowed for in the succeeding loadings, the load being always applied in tons per square inch of actual section.

Diagram No. 2 shows the elastic properties of the same steel after it had been heated to 500°, to 650°, and to 700° C., and quenched in water at about 15° C. Each of the specimens employed was broken by a single continuous loading. Curves A and B show that quenching from 500° and from 650° C. had little effect on the elastic properties of the steel. The specimen from which Curve B was obtained had been more thoroughly annealed before quenching than Specimen A, and this may account for the lower breaking load and greater ultimate extension obtained with Specimen B, although all the specimens employed were primarily annealed. Curve C shows that a marked change was produced in elastic properties by quenching from 700° C.

DIAGRAM No. 2.—(Mild steel-quenched.)

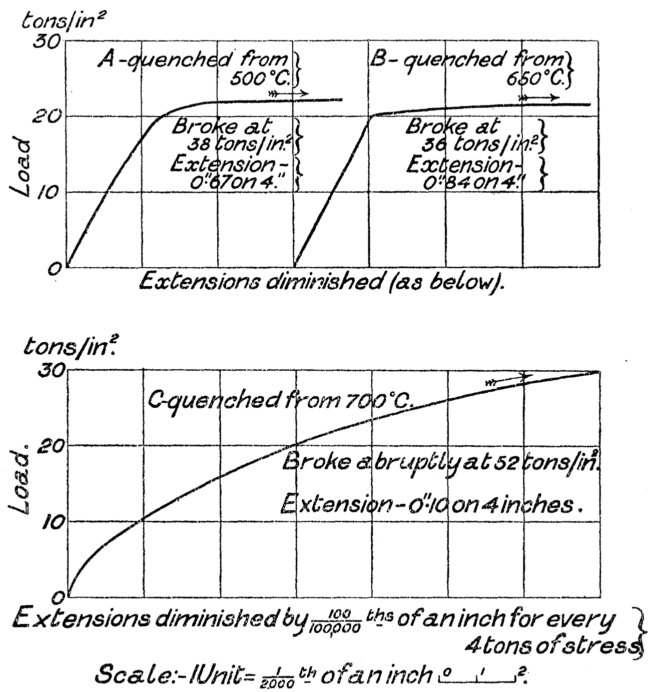
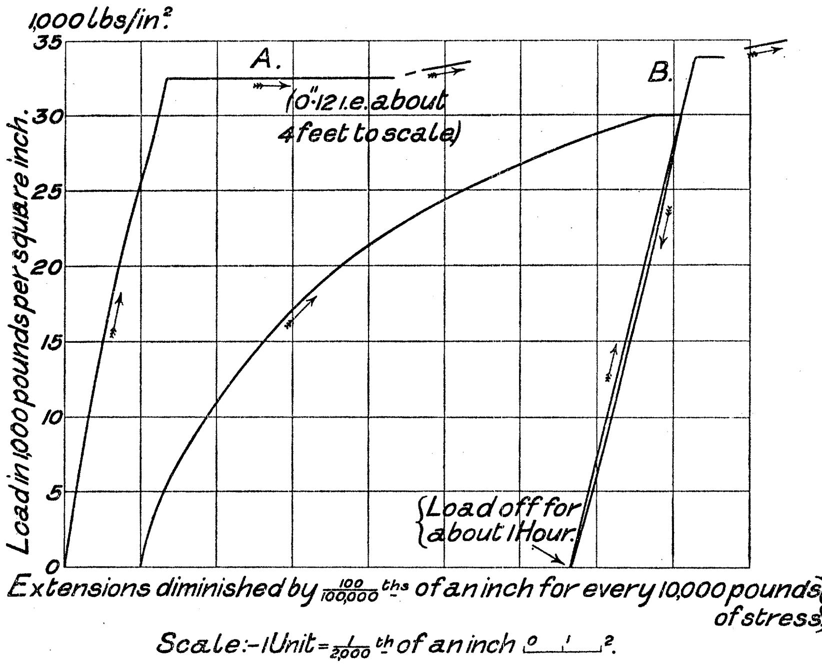


Diagram No. 3 shows the effect produced on the elastic properties of Lowmoor iron by quenching from 700° C. Curve A was obtained from an annealed specimen of the material. A very clearly defined yield-point is shown at the stress of 33,000 lbs. per square inch. After the yielding at the yield-point had spread throughout the specimen, the load was steadily increased until fracture occurred at the stress of 50,300 lbs. per square inch. The extension produced was 0″·95 on 4 inches, neglecting all the local extension which occurred at the point of fracture, or 1″·23 including the local extension.

Curve B, which was obtained from a specimen which had been quenched from 700° C., clearly shows the loss of elasticity produced by quenching. A curious recovery effect was noticed in this test. The load was applied until a stress of 30,000 lbs. was attained, and

DIAGRAM No. 3.—(Lowmoor Iron.)



Diameter of specimens A and B = 0″·44.
Length under test = 4″·00.

Specimen A.—Annealed at 750° C. Broke at 50,300 lbs. per square inch. Extension 0″·95 omitting, or 1″·23 including, local extension.

Specimen B.—Heated to 740° C., slowly cooled to 700° C., and then quenched in cold water. Broke at 61,300 lbs. per square inch. Extension 0″·61 omitting, or 0″·88 including, local extension.

was then removed. The contraction which occurred on the removal of the load was almost perfectly elastic. Had the load been immediately replaced, the material would have shown perfect elasticity up to the stress of 30,000 lbs., but immediately the load was increased beyond this amount larger yielding would have occurred, and a smooth continuation of Curve B would have been obtained. The specimen was, however, allowed to rest for about an hour before the load was replaced and increased. This rest proved to have a comparatively large effect, the material showing very perfect elasticity up to the stress of 34,000 lbs. per square inch. At this stress a partial yield-point was exhibited (represented by about 6 units of extension on the diagram), and on increasing the load gradual extension was produced, until ultimately fracture occurred at the high stress of 61,300 lbs. per square inch. The ultimate extension is marked at the foot of the diagram, and was less than that obtained with annealed material.

It may be recorded that another specimen of this Lowmoor iron was quenched from 700° C., but, before testing, this specimen was re-heated to about 200° C. in order to see if any appreciable return to the elastic condition illustrated by Curve A, Diagram 3, would be obtained. The behaviour of the specimen was more nearly elastic for low loads than is shown by Curve B, but all the main features of Curve B were corroborated; gradual departure from Hooke's law was obtained until fracture occurred at 61,500 lbs. per square inch, the extension being $0''\cdot54$ on 4 inches omitting, or $0''\cdot9$ including, local extension.

Before leaving the consideration of iron and steel, the effect produced by quenching iron, as illustrated by compression tests, may next be considered.

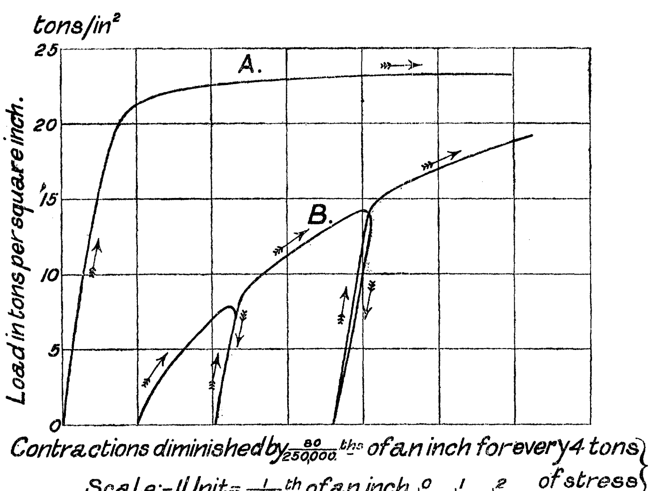
Diagram No. 4 shows by a comparison of two compression curves the change in elastic properties produced by quenching mild steel from a red heat. Specimen A, was a short annealed block of mild or semi-mild steel; the diameter of the specimen was $1''\cdot156$ and its length $1\frac{7}{8}$ inches. The compression instrument employed enabled the contraction on a length of $1\frac{1}{4}$ inches to be measured to the $\frac{1}{250000}$ of an inch. Curve A shows that the annealed material was elastic up to the stress of 21 tons, but 23 tons per square inch had to be applied before really large yielding occurred. A tension test of this material showed a well-defined yield-point at $22\frac{1}{2}$ tons per square inch.

Specimen B was exactly similar to Specimen A, but the material in this case instead of being annealed was heated to redness and quenched in cold water. Curve B shows the marked loss of electricity produced by the quenching. The rounding of Curve B at the two points where the load was removed is probably to be accounted for by experimental errors of the nature of back-lash in the testing machine or compression instrument.

Diagram No. 5 illustrates the results obtained by experiments with

copper rods. Curve A of that diagram was plotted from a tensile test made with the material in the condition as supplied. Curve B shows the elastic properties of the material after it had been heated to 630° C., and allowed to cool slowly, while Curves C_1, C_2, and C_3 show the effect produced by quenching the copper from 500° C., from 550° C., and finally from 600° C. Specimen B showed more perfect elastic behaviour for low loads than Specimen A, but large extension is shown by Curve B to have occurred earlier with the annealed material. Specimen C was first heated to 500° C., and quenched in cold water.

DIAGRAM No. 4.—(Mild steel under compression.)



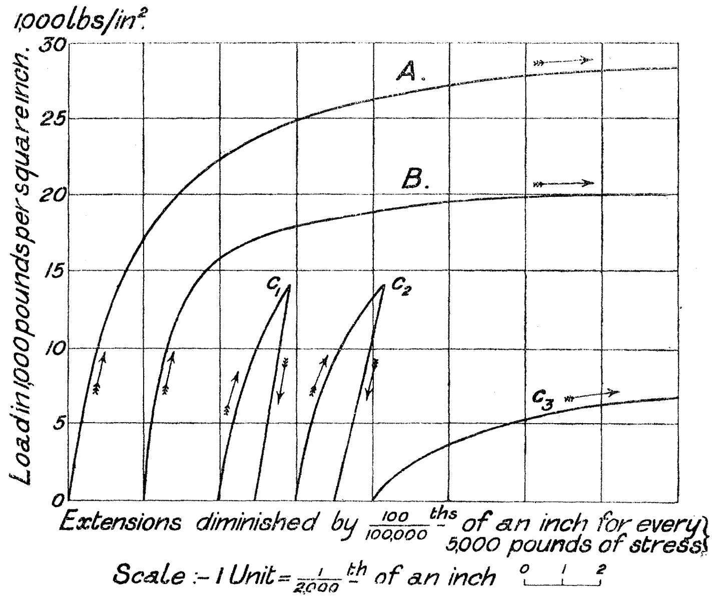
Specimen A.—Annealed.
,, B.—Quenched from a red heat.

Diameter of specimens = 1·16 inches.
Total length = $1\frac{7}{8}$ inches.
Contraction measured on $1\frac{1}{4}$ inches.

Curve C_1 was then obtained by applying and removing a load of 15,000 lbs. per square inch. The specimen was next quenched from 550° C., and Curve C_2 shows the slightly greater loss of elasticity which was thus produced. Curve C_3 shows the large effect caused by quenching the Specimen from 600° C. The breaking stresses obtained with the three specimens were 35,300, 33,500, and 32,300 lbs. per square inch of original area. These stresses were equivalent to 41,600, 40,800, and 44,200 lbs. per square inch, when allowance was made for the diminutions in area due to the large extensions of the specimens before fracture. These corrections were made by

calculating the reduced areas from the extensions obtained (omitting the local extensions at points of fracture) and neglecting the small changes in density which are known to be produced by stretching. Copper thus resembles iron and steel in having its breaking stress

DIAGRAM No. 5.—(Copper.)



Diameter of specimens = 0″·37. Length under test = 4″·00.

Specimen A.—Copper as supplied. Broke at 35,300 lbs. per square inch original area, or after an actual stress of 41,600 lbs. per square inch had been applied to the bar. Extension on 4 inches, 0″·74 omitting, or 1″·04 including, local extension.

Specimen B.—Heated to 630° C. and slowly cooled. Broke at 33,500 lbs. per square inch original area, or 40,800 lbs. per square inch actual stress. Extension on 4 inches, 0″·87 omitting, or 1″·25 including, local extension.

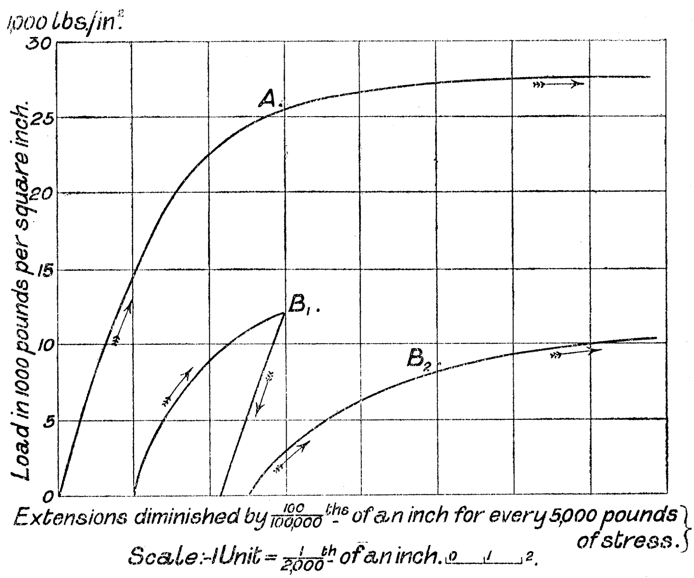
Specimen C.—Quenched from 500°, 550°, and then from 600° C. Broke at 32,300 lbs. per square inch original area, or 44,200 lbs. per square inch actual stress. Extension on 4 inches, 1″·50 omitting, or 1″·98 including, local extension.

increased by quenching, but differs from iron and steel in giving a greater extension before fracture when in the quenched condition. The abrupt yield-point which is so striking a feature in the testing of annealed iron and steel, is not exhibited with copper. The ultimate extensions obtained with the three specimens of copper tested were 0″·74 on 4 inches with A, 0″·87 with B, and 1″·50 with C, omitting

the local extensions at the points of fracture, or 1″·04, 1″·25, and 1″·98 respectively including the local extensions.

Diagrams Nos. 6 *and* 7 may now be given without comment. They illustrate tests made with brass and aluminium, and it is shown in both cases that there is a loss of elasticity produced by quenching. When the quenched material has been once loaded it is brought approximately into the elastic condition, so that from a removal and reapplication of load a straight stress-strain curve is obtained.

DIAGRAM No. 6.—(Brass.)



Diameter of specimens = 0″·44. Length under test = 4″·000.

Specimen A.—Brass as supplied. Broke 4 times in machine grips at about 48,500 lbs. per square inch. Extension from 0″·87 on 4 inches after the first break to 1″·68 after the fourth.

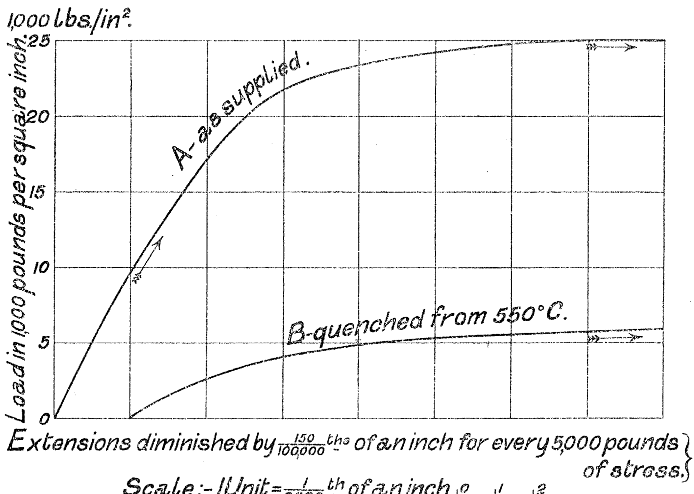
Specimen B.—Brass quenched from 600° C. (B_1) and from 700° (B_2). Broke at 42,500 lbs. per square inch after two breaks in the machine grips at slightly lower stresses. Extension, 1″·33 on 4 inches.

Three specimens of zinc, of diameter 0″·40, were also tested. The first—in the condition as supplied—broke at 21,000 lbs. per square inch, the ultimate extension being 2″·04 on 4 inches. There was great local extension, the specimen being drawn to a very narrow neck before fracture. The second specimen was quenched from 350° C. It yielded rather more for the lower loads than the first specimen, and broke at 20,500 lbs. per square inch with an extension of 0″·41 on 4 inches. The fracture was quite abrupt, so that there was little or no

local extension. The third specimen was heated to 350° C., and allowed to cool in the air. The behaviour of this specimen was very similar to that of the quenched specimen. Rather less yielding was obtained at low stresses, fracture occurred at 21,400 lbs. per square inch, the ultimate extension was 0″·68 on 4 inches. The fracture was abrupt, so that there was practically no local extension.

Two specimens of cast tin were also tested, but owing to the low melting point of tin quenching from 200° C. could only be tried. The

DIAGRAM No. 7.—(Aluminium.)



Diameter of specimens = 0″·35. Length tested = 4″·00.

Specimen A.—As supplied. Broke four times in machine grips at 28,500 lbs. per square inch. Extension 0″·14 on 4 inches.

Specimen B.—Quenched from 550° C. Broke in the machine grips at 23,200 lbs. per square inch. Extension 0″·9 on 4 inches.

quenched specimen showed rather greater extension at the lower stresses; both specimens broke at 5250 lbs. per square inch; the extensions were 0″·5 and 0″·8 on the 4-inch lengths, but local extension occurred in several places before fracture.

In conclusion, it is proposed to consider how far the effects produced by quenching described above may be accounted for by the stresses set up in the material by the sudden cooling and consequent contraction, the material, after quenching, being no longer in what has been termed its "state of ease."

When a long cylindrical rod cools, the cooling takes place radially, and the end effects may be neglected. Taking any cross-section of the rod, the outside ring will cool first and assume its elastic state; the

interior will then contract, and exert a radial pull on the outside solidified layer. This will put the material into a state of circumferential compression. If the tangential direction be called the direction of X, the radial direction that of Y, so that the rod considered lies along the axis of Z, then the material in the outside layer of the quenched rod of metal is subjected to a compressional stress in the X direction. If a layer of material be considered at some distance from the outside it will be found to be subjected not only to a compression in the X direction, but also to a tension in the Y direction. For the outside solidified layers are able to resist to some extent the radial pull due to contraction. A particle of material at a point such as A will thus be subjected to stresses p and t in the manner illustrated in the sketch. Going nearer the centre of the bar, the pull due to contraction of the hot material may be more than balanced by the outward radial pull due to the solidified material which has settled down under radial tension, so there may be a resultant outward pull all round the layer considered, and a particle such as B will be subjected to a circum-

ferential pull, t', as well as a radial pull, t. There will be, of course, a gradual transition from material in the one condition to material in the other.

Further, the stresses induced by sudden cooling will probably be severe enough to overstrain many layers of material, and, except in the case of portions which have been overstrained when quite cool, recovery from overstrain will be effected, so that the material will be left in an elastic condition, hardened as regards the stresses in question, and not in the semi-plastic state typical of material which has been recently subjected to overstrain.

Now it is well known that when metals are deformed they alter very little in volume, almost the whole strain is one due to change of shape. It is only necessary then to consider the shear stresses applied by the systems of stresses illustrated above at A and B. A pull (t or t') is equivalent to a hydrostatic tension ($\frac{1}{3}t$ or $\frac{1}{3}t'$) and two shear stresses in definite directions; a push (p) gives rise to a hydrostatic pressure ($\frac{1}{3}p$) and two shear stresses. A circumferential pressure (p case A) gives rise to the following two shears :—

1_A, giving contraction in direction of X and extension in direction of Y,
2_A " " " X " " Z.

A radial tension (t cases A and B) gives rise to the following two shears:—

1_{AB}, giving extension along Y and contraction along Z,
2_{AB} " " " Y " " X.

A circumferential tension (t' case B) gives rise to the following two shears:—

1_B, giving extension along X and contraction along Y,
2_B " " " X " " Z.

It is necessary then to consider what effect these shear stresses, induced by quenching, have on the behaviour of a bar subjected to a tension (T) or a pressure (P) in the direction of the Z axis.

A pull, T, in direction of the Z axis gives rise to the following two shears:—

1_T producing extension along Z and contraction along X,
2_T " " " Z " " " Y.

A push, P, along the Z axis produces the following two shears:—

1_P giving contraction along Z and extension along X,
2_P " " " Z " " " Y.

It will thus be seen that the shear stresses induced in a bar of metal by sudden cooling have the effect of weakening certain layers of the bar as regards resistance to tension, and certain layers as regards resistance to compression. For the shear stress 1_T is applied along the same series of parallel planes as the stress 2_A, and although the stress 2_T is directly opposed by the stress 1_{AB}, the "yielding" of the material must be determined by its strength in the weakest direction. Similarly the stresses 1_P and 2_P are in the same directions as the stresses 2_B, 1_{AB}, so that the loss of elasticity exhibited by quenched material both as regards tension and compression has been accounted for. It may, however, be desirable to consider a little in detail what ought to be the behaviour under tension of, say, a bar of iron which has been subjected to the system of stresses described above. At the commencement of the loading the stress due to the applied load will be uniformly distributed over the whole section, but as soon as a very small load is applied, a long cylindrical layer of material (A′), which has been left by the sudden cooling under a stress of type 2_A very nearly equal to the "yielding" stress of the material, will yield. This yielding would continue to the enormous extent characteristic of a yield-point were all the material in the condition A′; but the weak layer, being surrounded by stronger material, the yielding is only allowed to continue to a very slight extent. This small yielding will, however, cause a redistribution of the internal stresses set up by quenching to

take place, and perhaps also a redistribution of the stress due to the applied load. This alteration in the distribution of the internal stresses must be such as to cause the surrounding strong layers to stretch elastically as far as the weak material has been permanently stretched. The alteration in the internal stresses will remain after the applied load is removed, as the material which has been permanently deformed will be unable to relieve the stronger material. The apparent permanent set which is shown with quenched material after the removal of applied load, may thus be due to the real permanent extension only of the weak layers, and to the elastic extension of the strong layers produced by the new distribution of internal stresses. This explanation, however, does not suffice, at least in the case of iron and steel, to explain the behaviour of a quenched rod under applied stress, for Diagrams 2 and 3 show that such a rod may be stretched further than is compatible with elastic extension—even supposing some of the iron to have been overstrained to the maximum in the most favourable direction, without stretching nearly far enough for the yield-point of the iron to have been passed. Hence in the case of iron and steel recourse must be had to the explanations which simply attribute the observed effects to the formation of allotropic modifications of the metal or to the changes caused by the transition of the carbon—always present—from one condition to another.

In conclusion, it may be recorded that pieces of the iron and steel specimens used in this research were polished, etched, and examined under the microscope. In the case of the steel specimens the change from the ferrite and pearlite structure shown with the annealed material to the martensite structure shown with the quenched steel was very striking. But in the case of the Lowmoor iron no difference was detected by the microscope in the structures of the annealed and of the quenched specimens, although, as shown by Diagram 3, the elastic properties in the two conditions were vastly different.

"Harmonic Tidal Constants for certain Australian and Chinese Ports." By THOMAS WRIGHT, of the Nautical Almanac Office. Communicated by Professor G. H. DARWIN, F.R.S. Received August 1, 1902.

Ballina (New South Wales), Princess Royal Harbour (King George's Sound), Newcastle (New South Wales), Brisbane (Queensland), and Sydney (New South Wales).

The tidal observations made at these five ports have been reduced by the aid of certain sums placed at my service by the Government Grant Committee of the Royal Society, and I am indebted to Professor